EFFECTS OF COW GREEN RESERVOIR UPON DOWNSTREAM FISH POPULATIONS

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Introduction

In 1967 the FBA began pre-impoundment studies on fish populations at the site of the proposed Cow Green reservoir in upper Teesdale, (Crisp, Mann & McCormack 1974). Post-impoundment observations were made from 1971 to 1980 and some routine observations are still in progress. The project is concerned with fish populations in the River Tees downstream of the reservoir, in the reservoir itself and in the afferent streams, but the present account is confined to effects within the river downstream of the dam.

A detailed account of physical and chemical effects was given by Crisp (1977) and a series of papers on effects upon invertebrates was reviewed by Armitage (1978a).

The reservoir

Cow Green reservoir is situated in the northern Pennines on the River Tees at Nat. Grid Ref. NY/813289 (Fig. 1). It has an area of 312 ha, a capacity of 40·9 $m^3 \times 10^6$, a top water level of 489 m O.D. and a maximum depth of 23 m. The catchment has an area of c. 5570 ha composed mainly of heather moor and blanket bog, but also containing areas of alluvial and limestone grassland.

The function of the reservoir is river regulation – collection of water during periods of high river flow (late autumn to spring) and release of water during dry periods (chiefly summer and early autumn) – so as to maintain suitable river levels for downstream abstraction. The annual yield is 72 $m^3 \times 10^6$ yr^{-1}, of which 14 $m^3 \times 10^6$ are released continuously as compensation flow (0·45 m^3 s^{-1}) and the remainder is released as required for river regulation.

The dam was first closed in June 1970 and by March 1971 the reservoir was filled to within 3 m of top water level. The first overflow via the spillway occurred during the winter of 1971-72.

As the reservoir is comparatively shallow and in an exposed position, stratification occurs rarely and is of brief duration.

The river

About 275 m downstream of the dam the River Tees flows over Cauldron Snout, a high (c. 60 m) waterfall over the edge of the Whin Sill intrusion. Maize Beck, a major tributary (catchment c. 4140 ha), joins

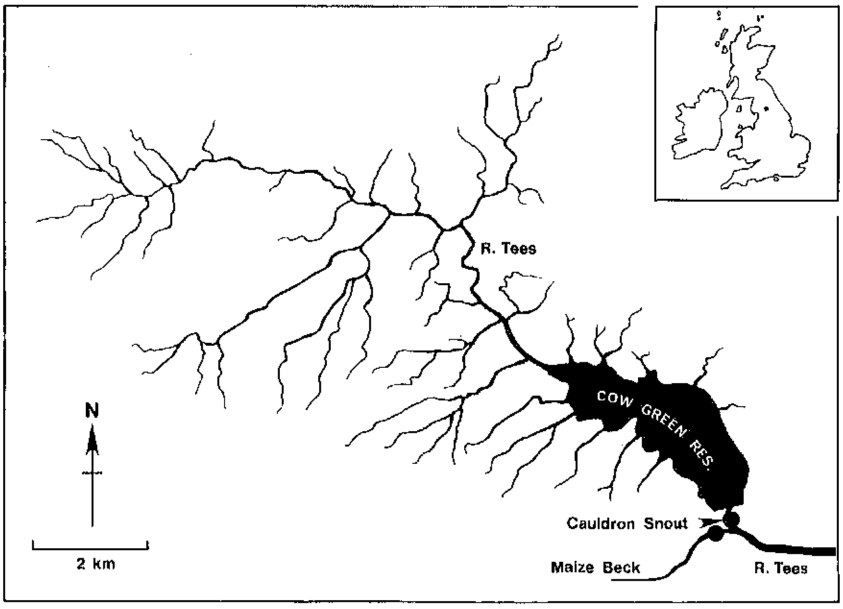

FIG. 1. Map of Cow Green reservoir and associated stream systems. The positions of the downstream census stations in the R. Tees and in Maize Beck are shown (●). Inset indicates the approximate position of the study area within mainland Britain.

the Tees about 630 m downstream of the dam and a further major tributary joins 5·5 km below the confluence of Maize Beck. As the entry of these large tributaries relatively close to the point of discharge from the reservoir was likely to reduce the effects of regulation upon the downstream fish populations, no attempt was made to assess the variation in impact with distance downstream. Instead, attention was concentrated on a reach of the Tees situated c. 590 m downstream of the dam and parallel observations were made in the lower reaches of the unregulated Maize Beck for comparison (Fig. 1).

The station in the River Tees has an annual mean discharge of 2·0 to 3·0 $m^3 s^{-1}$, is about 15 m wide and 0.2 to 1.0 m deep. The bed consists chiefly of large boulders (0.3 to 1·5 m diameter) and occasional patches of smaller stones. The Maize Beck station has an annual mean discharge of 1·7 to 2·6 $m^3 s^{-1}$, a width of c. 20 m and is 0·1 to 0·7 m deep. The bed consists of rather smaller boulders than in the Tees station and patches of smaller stones occur more frequently.

Before regulation of the Tees, both of these reaches contained negligible amounts of vegetation, and streamers of filamentous algae which did develop on the stones during low flows were rapidly scoured off by spates. After regulation, a dense and relatively permanent growth of algae and mosses (*Fontinalis* sp.) developed on the boulders within the Tees station.

Physical and chemical effects of regulation

1. *River discharge*

Before impoundment, the Tees at Cow Green was subject to large and rapid fluctuations of discharge and the main effect of regulation was to reduce the size of the fluctuations. Before regulation, discharges of less than 0·1 times the annual mean discharge occurred on 20% of the days in a year. Such low discharges did not occur after regulation began. Similarly, in the natural river discharges of more than 5 times the annual mean discharge occurred on average once per month, but after regulation the occurrence of discharges greater than 5 times the annual mean discharge was considerably reduced and discharges greater than 8 times the annual mean were eliminated (Fig. 2).

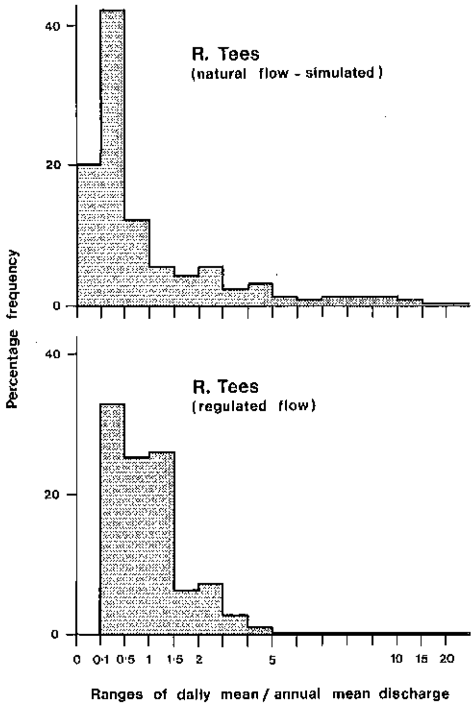

FIG. 2. Frequency distributions of daily mean discharges expressed as proportions of annual mean discharge in the natural River Tees (computer simulation) and in the regulated Tees (observed data). From Crisp (1977).

2. *Water temperature*

The main effects of reservoir storage upon the temperature of the released water, as compared with the temperature in the unregulated tributary, are shown in Fig. 3 and can be summarized as:

(a) Lowering of the summer temperature peak by 1 to 2 °C.

(b) Delay of the rise in temperature in spring by 20 to 50 days and of the fall in autumn by 0 to 20 days.

(c) Substantial reduction of diel temperature fluctuations.

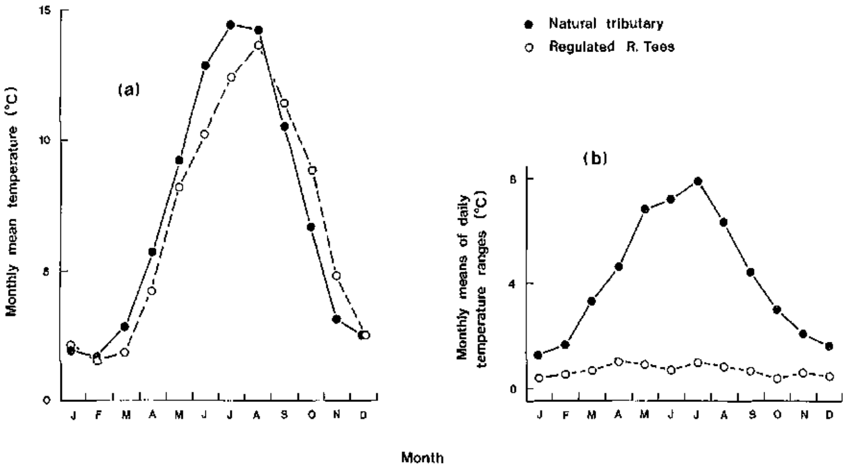

FIG. 3. Monthly means of daily temperature means (a) and of daily temperature ranges (b) in the River Tees downstream of the dam site after regulation (○) and in the unregulated Maize Beck (●). From data in Crisp (1977).

It is likely that these effects will be reduced as the water passes downstream from the point of release. However, 144 'spot' readings of temperature were taken over a three-year period at the fish census station c. 590 m downstream of the dam and on all but two occasions the temperature was within the range +1·7 to −1·2 °C of the outfall temperature. Reservoir storage causes reduced diel temperature fluctuations at the R. Tees station, as compared with the Maize Beck station (Fig. 4a). Results in Northumbrian Water Authority (1976) show that, although diel fluctuations at the Tees station were substantially reduced during compensation releases (0·45 $m^3\ s^{-1}$), even greater reductions occurred during regulation releases of 3·5 to 6·6 $m^3\ s^{-1}$.

3. *Dissolved oxygen concentration*

In general, the water within the reservoir was well mixed. Oxygen concentrations of less than 70% saturation were rarely recorded at any

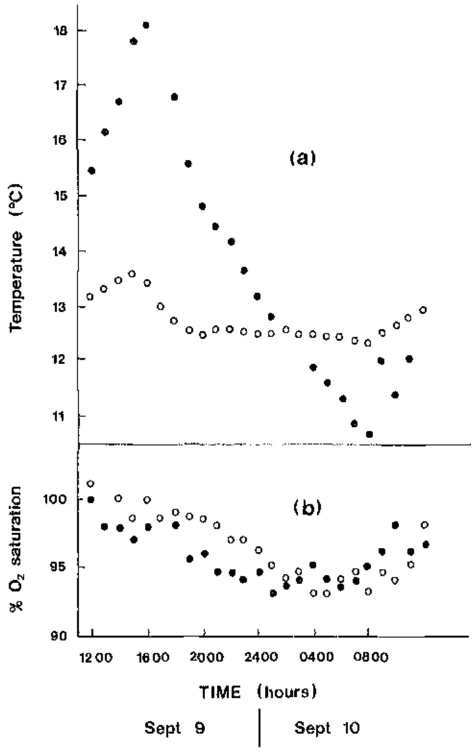

FIG. 4. Hourly values of water temperature (a) and oxygen content as a percentage of saturation (b) in the regulated Tees (○) and the unregulated Maize Beck (●) from 1200 hours on 9 September 1971 to 1200 hours on 10 September 1971. Redrawn from Crisp (1977).

depth and values greater than 80% were more usual. In consequence, the water released from the reservoir was well oxygenated and further oxygen was taken up between the point of release and the fish census station. For example, during the afternoon of 4 September 1973 reservoir water at draw-off level had an oxygen concentration of 87·5% saturation. Values at the valve outfall, at a point 200 m downstream and at the fish census station (590 m downstream) were 90·0, 95·0 and 96·0% respectively.

Diel fluctuations of oxygen concentration were small (Fig. 4*b*) and there is no evidence that the post-regulation growth of vegetation in the Tees had any effect on the size of the fluctuations.

4. *Ionic concentrations*

Monthly water samples taken at the reservoir inflow and outflow between April 1975 and March 1976 covered a wide range of discharge

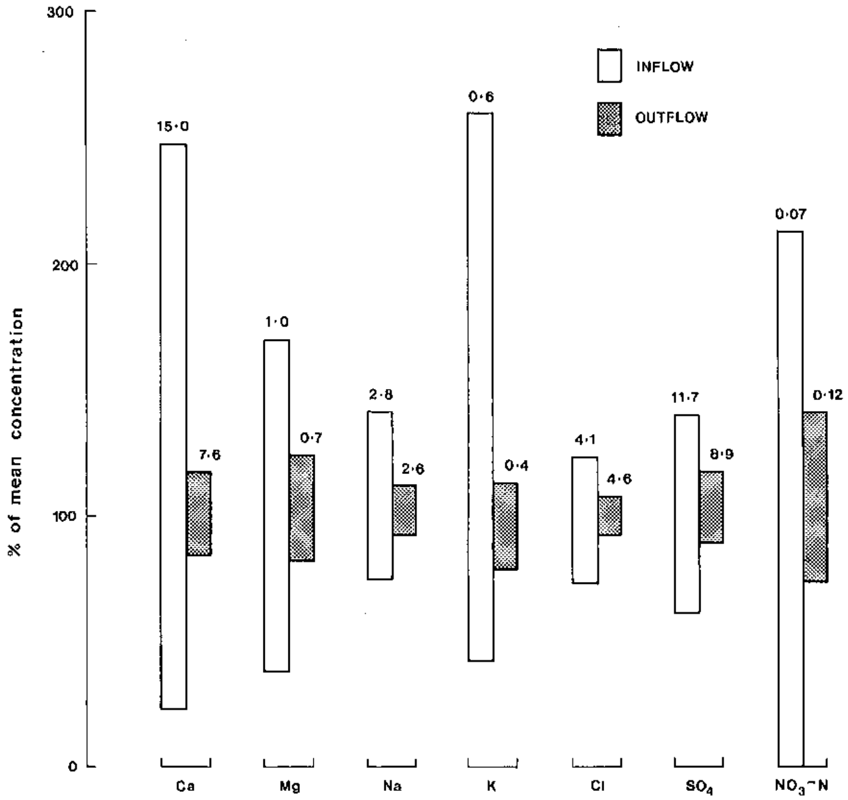

FIG. 5. Observed range of concentrations of each determinand, expressed as percentage of the mean value. The mean value (mg l^{-1}) is shown above each histogram. From data in Crisp (1977).

conditions. The ionic concentrations at the inflow showed considerable variation (Fig. 5) and the fluctuations could be approximately related to discharge fluctuations. A similar pattern was observed in a small tributary of the Tees (Crisp 1966). In contrast, concentrations at the outflow were less variable and followed a seasonal pattern.

Fish populations

The fish populations before regulation were described by Crisp et al. (1974). Two species, the brown trout (*Salmo trutta* L.) and the bullhead (*Cottus gobio* L.) occurred regularly in the R. Tees station and in Maize

Beck. Small numbers of minnows (*Phoxinus phoxinus* (L.)) were found in both reaches at infrequent intervals, probably as strays from other habitats in the vicinity.

Within the area downstream of the dam, fish census work was carried out three times per year (May, August and October) from August 1967 to October 1975, and some additional observations and collections of material were made between 1976 and 1980. The data have been arbitrarily divided between three periods: (a) pre-regulation, August 1967 to May 1970; (b) transition, August and October 1970; (c) post-regulation, May 1971 onwards. Comparisons have been made between the pre- and post-impoundment periods.

1. *Age and growth*

Trout No clear-cut change in the growth of trout, following regulation of the Tees, could be seen from inspection of observed mean lengths-for-age or of mean lengths back-calculated from scale lengths. However, the data can be examined more precisely by comparison of linear regressions of the logarithm of instantaneous growth rate in length (G_l) during each year upon length at the start of that year. Such an analysis showed that, following regulation of the R. Tees, there was a small but statistically significant increase in the instantaneous growth rate of trout in the Tees but not in Maize Beck (Crisp et al., 1983).

Bullhead Observed lengths-for-age (based on otolith readings) of bullheads in the two stations indicate a reduction in the lengths of O

TABLE 1. Mean lengths of O group bullheads in Maize Beck and in the River Tees before and after regulation of the R. Tees. From Crisp et al. (1983).

	Mean length (cm)			
	Maize Beck		*R. Tees*	
Month	*Pre-regulation*	*Post-regulation*	*Pre-regulation*	*Post-regulation*
August	2·6	2·3	2·2	1·6
October	3·8	3·3	3·1	2·7
May	4·4	4·3	3·7	3·5

group fish in August and October after regulation of the Tees (Table 1). The reduction was more marked in the Tees than in Maize Beck and may reflect later oviposition in the Tees as a result of the changed water temperature regime. There is, however, no evidence of changes in the growth of older bullheads as a result of regulation.

2. *Population estimates*

The electrofishing equipment (Moore 1968) used for the fish census work was designed primarily for use in small streams. The equipment was close to its useful limit in larger streams such as the R. Tees and Maize Beck, especially during moderate spates. In Maize Beck throughout the study and in the Tees before impoundment, care was taken to ensure that population estimates were obtained during relatively low discharges. However, this was not always possible in the regulated Tees.

Trout In Maize Beck the population density of brown trout showed no significant change. In the Tees the mean population density after regulation was about 140% of the value before regulation (Table 2) and the difference was greater than could be accounted for by chance. However, this might well be an underestimate of the magnitude of the change because some of the post-regulation estimates from the Tees were obtained during high ($>1{\cdot}5$ m^3 s^{-1}) discharges and there was strong evidence that estimated population densities were low when discharge was high and vice-versa. This implies either that trout moved into the reach during low discharges and out again during high discharges, or that at high discharges the efficiency of the electrofishing was impaired and underestimates of the population were obtained.

TABLE 2. Summary of estimated minimum population densities of brown trout before and after regulation of the Tees. The mean number of fish 100 m^{-2} over the whole of each period is shown followed, in parentheses, by the range of observed values.

	Maize Beck	*River Tees*
Pre-regulation (August 1967 to May 1970)	2·0 (0·4 to 5·0)	3·5 (1·4 to 5·1)
Post-regulation (May 1971 to October 1980)	1·8 (0·4 to 4·0)	4·9 (1·9 to 8·1)

Bullhead Population densities of bullhead fry varied considerably from year to year but were generally higher in the Tees (0–90 in 100 m^2) than in Maize Beck (0–20 in 100 m^2). The data are inadequate for detailed analysis.

TABLE 3. Summary of estimated minimum population densities of bullheads, other than O group, before and after regulation of the Tees. Other details as in Table 1.

	Maize Beck	*River Tees*
Pre-regulation (August 1967 to May 1970)	4·2 (2·3 to 7·8)	9·9 (5·1 to 19·4)
Post-regulation (May 1971 to October 1980)	5·8 (0·7 to 13·8)	33·4 (11·4 to 93·8)

A summary of information on population densities of older bullheads (Table 3) shows that post-regulation densities in the Tees were about three times the pre-regulation value and this difference was statistically significant. A slight increase in the estimated population density in Maize Beck could have been due to chance.

As for the trout, the estimates for the Tees after regulation were negatively correlated with river discharge.

3. *Reproduction*

Trout Before regulation most female trout in the stations downstream of the dam matured during the third year of life and their annual egg output (fecundity) could be related to the length of the fish by the equation $f = 0{\cdot}399\ l^{2{\cdot}092}$, where f = fecundity and l = fish length in cm. No changes in the age at first sexual maturity or in the length : fecundity relationship could be detected after regulation. This may reflect the relatively small numbers of sexually mature fish found.

Bullhead No change in age at first sexual maturity or in the relationship between fish length and fecundity could be detected amongst the Maize Beck bullheads. In the Tees there was a decrease in the fecundity of individual fish so that the egg output of females of 6 to 8 cm length (such fish form 80–95% of the population of female spawners) was reduced by 7·5% to 30%. At the same time, the age at first sexual maturity decreased (50% mature at age II before regulation and 84% mature at age II after regulation). The net result of these changes, together with the observed increase in population density, was an increase in estimated population fecundity from 230 to 840 eggs m^{-2} $year^{-1}$.

4. *Instantaneous rate of loss*

In an entire fish population or in a sub-population in which recruitment by immigration and loss by emigration are approximately in balance, the slope of a straight line relating the logarithms of number of survivors to time gives (subject to certain statistical conditions) an estimate of the instantaneous rate of mortality in the population. Recruitment to the trout populations of the Tees and Maize Beck stations was mainly by immigration, chiefly by fish less than 30 months old before regulation and by fish less than 24 months old after regulation, and analyses of instantaneous rate of loss (i.e. mortality + emigration − immigration) can only be made for older trout. For bullheads it is more reasonable to assume that emigration and immigration are negligible or equal but it is still safest to assume that the calculated rate is a rate of 'loss' rather than purely of mortality.

Trout The estimated instantaneous rate of loss was about 0·7 $year^{-1}$ in the River Tees and about 0·9 $year^{-1}$ in Maize Beck and no statistically significant change could be shown in either station as a result of regulation.

Bullhead In Maize Beck before and after regulation and in the Tees before regulation estimated instantaneous rate of loss was 0·67 to 0·81 and no statistically significant differences could be demonstrated. However, rate of loss in the Tees after regulation was 1·30 and this was significantly higher than the value for this station before regulation.

5. *Production*

Trout Approximate estimates suggest that trout production in Maize Beck was 0·15 g m^{-2} $year^{-1}$ both before and after regulation of the Tees, whilst in the R. Tees production increased from 0·3 to 0·4 g m^{-2} $year^{-1}$ after regulation. (The available data are too imprecise for detailed analysis).

Bullhead Estimated production in Maize Beck was 0·40 g m^{-2} $year^{-1}$ before and 0·55 g m^{-2} $year^{-1}$ after regulation of the R. Tees. Corresponding values for the Tees were 1·06 and 3·64 g m^{-2} $year^{-1}$, respectively. The increase in production in the R. Tees was caused mainly by a large increase in the contribution of O and I group fish to total production.

Stomach contents of fish

A description of changes in the stomach contents of fish in the Tees, following regulation, was given by Crisp et al. (1978)*.

There are various methods for expressing the results of stomach contents analyses. Hynes (1950) compared various methods and finally used a points system, though he commented that the percentage occurrence and the numerical composition methods gave similar results. For the Cow Green data the analyses of stomach contents were expressed as percentage numerical composition based on counts of the number of individuals of each prey taxon in the stomach. This method was relatively simple to apply and gave results which could be directly compared with data on benthos composition.

In the Tees after regulation very large numbers of micro-crustacea occurred in some trout stomachs. If these had been expressed on a percentage numerical composition basis they would have dominated the analyses and obscured changes in the proportions of larger animals in the stomach contents. Therefore, micro-crustacea were omitted from the percentage composition analyses and considered separately.

Trout

Following regulation of the Tees, there was little change in the stomach contents of trout in Maize Beck. In the Tees the percentage of Ephemeroptera increased by a factor of 1·5 to 6 and the percentage of terrestrial material decreased to between half and three quarters of its former value.

* Please note that in the published version of this paper Figure 2 appears on p. 289 above the legend for Fig. 1 and Fig. 1 appears on p. 291 above the legend for Fig. 2.

On a more detailed level, in the Tees stomachs several groups showed changes in the proportions of various species and genera following regulation. The most striking were:

(i) Ephemeroptera

Before regulation 80% of the Ephemeroptera in stomachs collected in August were *Baetis* spp. and 5% or less were *Ephemerella ignita* (Poda). In stomachs collected in May and October, 15 to 75% of the Ephemeroptera were Ecdyonuridae. After regulation *Baetis* predominated in May and October stomachs (99 to 100%), and in August *Baetis*, Ecdyonuridae and *E. ignita* contributed 40, 40 and 20% respectively.

(ii) Diptera

Simuliidae and Chironomidae were equally numerous in pre-regulation stomachs but Chironomidae formed 90% or more of the Diptera in stomachs collected after regulation.

(iii) Trichoptera

There was an increase in the importance of *Brachycentrus subnubilus* (Curt.) and Polycentropodidae, relative to other Trichoptera, after regulation.

Micro-crustacea were absent from trout stomachs before regulation. After regulation large numbers of micro-crustacea, chiefly Cladocera, were discharged from the reservoir (Armitage & Capper 1976) and also appeared in the stomachs of trout in the Tees. No zooplankton was found in the stomachs in May and this might be expected as the population density of Cladocera within the reservoir was low at this time of year. During August and October large quantities of zooplankton were present in the reservoir but this was only reflected in the trout stomach contents on six out of ten occasions when stomachs were collected for analysis. In fact, zooplankton was only found in the stomachs when water was being discharged from a valve within 11 m of the water surface. On these occasions micro-crustacea were found in 10–40% of stomachs and the mean number of individuals per stomach varied from 6 to 190.

Bullhead

The prey items in the stomachs of bullhead fry were similar to those in the stomachs of older specimens, apart from the fact that some of the larger items (e.g. Mollusca) were less numerous in the stomachs of fry than in the stomachs of older fish.

The data for older bullheads suggest that regulation of the Tees caused an increase in the importance of Mollusca and a decrease in the importance of Ephemeroptera and Plecoptera in the diet. Changes in the proportions of various species and genera of Ephemeroptera in the stomachs showed a generally similar pattern to that observed in trout stomachs.

Despite the presence of large quantities of drifting micro-crustacea in the regulated Tees at certain times of year, none of this material was found in bullhead stomachs.

Discussion

The time of impoundment at Cow Green coincided with the start of a series of unusually mild winters (1970–71 to 1975–76 inclusive) in the study area and this covered the period of intensive studies in the downstream stations (Crisp et al. 1983). The use of Maize Beck as an unregulated stream for comparison with the regulated River Tees was, therefore, valuable in ensuring that observed changes in the Tees were attributable to the effects of regulation rather than to coincident phenomena (e.g. the series of mild winters) which might have been expected to cause similar changes in both of the downstream stations. The entry of sizeable tributaries relatively close to the point of regulation precluded detailed studies of the reduction of the effects of regulation with distance downstream. Few data are available on this subject.

Both bullhead and trout population densities increased in the R. Tees after impoundment, whereas changes in growth rate were either undetectable or very small. The observed growth rates of trout, both before and after regulation, were about 80% of the values on maximum rations predicted from observed water temperatures and the equations of Elliott (1975). This supports the suggestion that water temperature rather than food supply may be the main factor limiting trout growth in the field (Edwards et al. 1979). It should also be borne in mind that trout in the Tees lose scales and some fin material during spates (hence a large proportion of the scales present are regenerated scales) and that the growth incurred in making good such damage is not included in estimates of net instantaneous growth rate. This, together with additional 'hidden growth' arising from the shedding of gonad products by sexually mature fish, would further narrow the gap between observed and predicted rates of growth. Armitage (1978b) showed that the standing crop of benthos increased in the Tees after regulation. An increase in the numbers and biomass of Mollusca was accompanied by a decrease in Ephemeroptera, but the most important change was that, after regulation, very large numbers of *Hydra* and Naididae built up in the Tees. This suggests an increase in available food for fish but information on benthic production and on acceptability of different types of benthic organism to fish would be needed to prove this. A hypothesis which explains these various observations is that conditions for fish in the Tees have improved since regulation, possibly, but not necessarily, as a result of improved food supply. However, growth is limited by temperature, and the improved conditions have been exploited by the fish through an increase in mean population density rather than through a marked improvement in the growth of individuals.

In general, the observed changes in the stomach contents of fish in the Tees following regulation are consistent with the observations on benthos of Armitage et al. (1974), Armitage (1976) and Armitage (1978b). Several interesting points arise:

1. The stomach contents of both trout and bullhead suggest that, as a result of impoundment, there has been an increase in the abundance of *Ephemerella ignita*, and this agrees with information on invertebrates caught in nets during electrofishing but not with the results of kick samples (Armitage 1978b). The stomach contents also suggest that changes have occurred in the timing of greatest abundance or availability to fish of Ecdyonuridae and Baetidae in the Tees, perhaps through changes in the timing of life cycles of individual species within these two taxa and/or through changes in the relative proportions of different species within each taxon. Data in Armitage et al. (1974) and Armitage (1976) suggest that such changes in the seasonal abundance of the taxa have occurred.

2. The main contributor to the increased population density of benthos in the Tees was the increase in numbers of *Hydra* and Naididae. Neither of these were detected in fish stomachs but it is not clear whether this is because these organisms were not taken by the fish or because they very rapidly became undetectable in the stomachs.

3. Large quantities of zooplankton, chiefly Cladocera, are discharged from the reservoir, particularly during late summer and autumn. Most of this material is incorporated into the bed of the river (as a direct or indirect source of food for benthic organisms) within a few kilometres of the point of release (Armitage & Capper 1976). Some of this material is taken directly by trout but there is no evidence that it is taken by bullheads. It is not clear why bullheads do not utilize this material. Armitage & Capper (1976) showed that the quantities of zooplankton discharged from the reservoir were low between December and June and peaked in July to October. This reflects abundance within the reservoir (Crisp et al. 1978). However, the data from trout stomachs suggest that, in addition to this seasonal effect, the quantity of Cladocera discharged from the reservoir may be substantially influenced, on a day-to-day basis, by the depth of the highest operating draw-off level relative to the depth distribution of the Cladocera.

The impacts of impoundments upon downstream fish populations have received very little attention in the United Kingdom, apart from several studies of the effects upon the movements of migratory salmonids. The world literature on the subject is more extensive and is best considered in terms of four environmental characteristics, namely: barriers to movement, river flow, water temperature and water chemistry (Brooker 1981). As a substantial natural barrier to upstream fish movement (Cauldron Snout) exists close to the dam site, the effects of Cow Green dam upon upstream fish movements can be considered negligible.

Some workers have noted an improvement in stocks and production of salmonids in the stabilized flows of regulated rivers (Lister & Walker (1966) for the chum salmon *Oncorhynchus keta*; Somme (1958) for Atlantic salmon and sea trout), but others (Havey 1974; Lillehammer & Saltveit 1979) observed no major changes in population size. The results from Cow Green show an increase in the mean population density of both trout and bullhead.

Although the downstream water temperature pattern was modified as a result of regulation at Cow Green, the changes did not result in any major change in the scope for growth of the fish. The effect of changed temperature regime upon fish growth will, however, vary from one impoundment to another, even within the U.K. For example, Edwards (1980) showed that temperature changes caused by impoundment of the River Elan (Wales) would cause an appreciable reduction in the growth of brown trout.

The Cow Green impoundment has modified the downstream pattern of variation in concentration of common ions but has had little effect on dissolved oxygen concentration. There is no evidence that any chemical changes have occurred which are likely to have any effect upon the fish. However, the possibility of harmful effects upon fish does exist in impoundments elsewhere, particularly where quantities of deoxygenated hypolimnetic water are released, through inadequate dilution of pollutants (Treharne 1963), depositions of iron and manganese (Edwards & Crisp 1982), generation of hydrogen sulphide within the reservoir (Wright 1967) and from low oxygen concentrations.

Acknowledgements

The author is indebted to all those members of the Cow Green team upon whose work this report is based. The figures were drawn by Mr T. Furnass and the typescript was prepared by Mrs D. Jones. Helpful comments on the draft were made by Dr R. T. Clarke and Dr P. D. Armitage.

References

Armitage, P. D. (1976). A quantitative study of the invertebrate fauna of the River Tees below Cow Green reservoir. *Freshwat. Biol.* **6**, 229-40.

Armitage, P. D. (1978a). The impact of Cow Green reservoir on invertebrate populations in the River Tees. *Rep. Freshwat. biol. Ass.* No. 46, 47-56.

Armitage, P. D. (1978b). Downstream changes in the composition, numbers and biomass of bottom fauna in the Tees below Cow Green reservoir and in an unregulated tributary Maize Beck, in the first five years after impoundment. *Hydrobiologia,* **58,** 145-56.

Armitage, P. D. & Capper, M. H. (1976). The numbers, biomass and transport downstream of micro-crustaceans and *Hydra* from Cow Green reservoir (Upper Teesdale). *Freshwat. Biol.* **6,** 425-32.

Armitage, P. D., MacHale, A. M. & Crisp, D. C. (1974). A survey of stream invertebrates in the Cow Green basin (Upper Teesdale) before inundation. *Freshwat. Biol.* **4,** 369-98.

Brooker, M. P. (1981). The impact of impoundments on the downstream fisheries and general ecology of rivers. *Adv. appl. Biol.* **4,** 91-152.

Crisp, D. T. (1966). Input and output of minerals for an area of Pennine moorland: the importance of precipitation, drainage, peat erosion and animals. *J. appl. Ecol.* **3,** 327-48.

Crisp, D. T. (1977). Some physical and chemical effects of the Cow Green (Upper Teesdale) impoundment. *Freshwat. Biol.* **7,** 109-20.

Crisp, D. T., Mann, R. H. K. & Cubby, P. R. (1983). Effects of regulation of the River Tees upon fish populations below Cow Green reservoir. *J. appl. Ecol.* **20,** 371-86.

Crisp, D. T., Mann, R. H. K. & McCormack, J. C. (1974). The populations of fish at Cow Green, upper Teesdale, before impoundment. *J. appl. Ecol.* **11,** 969-96.

Crisp, D. T., Mann, R. H. K. & McCormack, J. C. (1978). The effects of impoundment and regulation upon the stomach contents of fish at Cow Green, upper Teesdale. *J. Fish Biol.* **12,** 287-301.

Edwards, R. W. (1984). Predicting the environmental impact of a major reservoir development. In *Planning and ecology* (ed. R. D. Roberts and T. M. Roberts), 55-79. London. Chapman and Hall.

Edwards, R. W. & Crisp, D. T. (1982). Ecological implications of river regulation in the United Kingdom. In *Gravel-bed rivers* (ed. R. D. Hey, J. C. Bathurst, & C. R. Thorne), 843-65. N.Y. Wiley.

Edwards, R. W., Densem, J. W. & Russell, P. A. (1979). An assessment of temperature as a factor controlling the growth rate of brown trout in streams. *J. Anim. Ecol.* **48,** 501-7.

Elliott, J. M. (1975). The growth rate of brown trout, *Salmo trutta* L., fed on maximum rations. *J. Anim. Ecol.* **44,** 805-21.

Havey, K. A. (1974). Effects of regulated flows on standing crops of juvenile salmon and other fishes at Barrows stream, Maine. *Trans. Am. Fish. Soc.* **103,** 1-9.

Hynes, H. B. N. (1950). The food of freshwater sticklebacks (*Gasterosteus aculeatus* and *Pygosteus pungitius*) with a review of methods used in studies of the food of fishes. *J. Anim. Ecol.* **19,** 35-58.

Lillehammer, A. & Saltveit, S. J. (1979). Stream regulation in Norway. In *The ecology of regulated streams* (ed. J. V. Ward & J. A. Stanford), 201-13. New York. Plenum.

Lister, D. B. & Walker, C. E. (1966). The effect of flow control on freshwater survival of chum, coho and chinook salmon in the Big Qualicum River. *Can. Fish Cult.* **37**, 3-21.

Moore, W. H. (1968). A light-weight pulsed D. C. fish shocker. *J. appl. Ecol.* **5**, 205-8.

Northumbrian Water Authority (1976). *Report on experimental releases from Cow Green Reservoir on the River Tees (23rd – 28th June 1976).*

Somme, S. (1960). The effects of impoundment on salmon and sea trout rivers. *IUCN 7th Technical Meeting, Athens,* 1, **4,** 77-80.

Treharne, W. D. (1963). Pollution problems on the Afon Rheidol. *Wat. Waste Treat. J.* March/April, 610-13.

Wright, J. C. (1967). Effects of impoundments on productivity, water chemistry, and heat budgets of rivers. In *Reservoir fishery resources Symposium.* 188-99. University of Georgia, Athens. American Fisheries Society.